The Beam Test of a 26 MHz ISR RFQ at Peking University *

Chen Chia-erh, Fang Jia-xun, Li Weiguo, Yu Jinxiang
Lu Yuanrong, Li Deshan, Yuan Jinglin, Wang Zhongyi
Dept. of Technical Physics and Inst. of Heavy Ion Physics,
Peking University, Beijing, China
H.Deitinghoff, H.Klein, A.Schempp
Inst. fuer Angewandte Physik, J.W.Goethe-Universitaet, D-60054
Frankfurt, Germany

Abstract

On the basis of an integral split ring (ISR) resonator, a flexible prototype radio frequency quadrupole (RFQ) accelerator with a tank diameter of 50 cm has been built at Peking University. It suits well to accelerate heavy ions at low frequency. The operating frequency can be adjusted in a range of 24 - 40 MHz by a movable shorting bar. The inter-electrode voltage reached 75 kV at an rf power of 42.5 kW with 1/6 duty factor and an energy gain of 300 keV has been obtained for N^+ ions as it was designed. The structure and rf properties of the ISR RFQ resonator, the beam dynamics and the experimental results of the beam tests are presented.

1. INTRODUCTION

Heavy ion RFQs have been developed rapidly in recent years with the increasing interest in injecting high current beams for inertial fusion studies and ion implantation in the areas of microelectronics and material modification [1,2]. However, heavy ion RFQs are much preferable to operate at lower frequency so as to get high beam transport efficiency. For this reason, the 4-rod spiral RFQ structure was developed at Frankfurt and LANL[3]. Based on the investigation of conventional split ring resonator, the ISR RFQ[4-6] has been developed at Peking University since 1984. The properties of this type of structure have been explored by a series of rf measurements on full scale models together with theoretical analysis. It turns out to be suitable for low frequency operation and feasible for heavy ion acceleration. A 26 MHz ISR prototype RFQ for accelerating N^+ ions up to 300 keV was designed, manufactured and tested at full power with beams, and will be discussed in detail as follows.

2. ISR RFQ RESONATOR

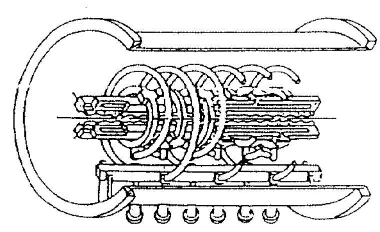

Fig. 1 A 26 MHz ISR RFQ

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The structure of the ISR RFQ resonator operating at 26 MHz is shown in Fig. 1. It consists of 3 pairs of right wounded and left wounded spiral arms connected to a common ground plate. The drift tubes in the conventional split ring cavities are replaced here by 4 quadrupole electrodes. The structure can be assembled as a whole outside the cavity and the electrodes can be replaced whenever necessary with fast easy. The whole structure is cooled by water flowing through the spiral tubes, supporting rings and quadrupole electrodes so as to reach high duty factor and hence high average beam current. The diameter and the wall thickness of the spiral tubes are 30 mm and 1.5 mm respectively, which turn out to be strong enough to ensure mechanical stability. The parameters of this RFQ are listed in Table 1.

Table 1 Principal parameters of a 26 MHz ISR RFQ

F	(MHz)	26
q/u		~1/14
Wi	(Kev/u)	1.5
Wf	(KeV/u)	21.4
Diameter	(cm)	50
Length	(cm)	90
V	(KV)	75
ρ	(KΩ-m)	204
Q		1,300

3. RF PROPERTIES

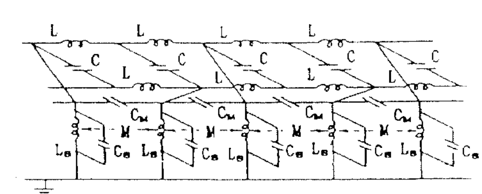

Fig. 2 Equivalent circuit of ISR RFQ

A lumped equivalent circuit of ISR RFQ resonator is shown in Fig. 2, where the rings are taken as a loaded λ/4 lines and the four electrodes as two pairs of coupled transmission lines. With the help of the equivalent circuit, the RF characteristics of the RFQ, including mode frequencies, Q value, and specific impedance can be calculated and predicted.[7] The rf power of the RFQ is fed by a linear power amplifier (XFD-D5) with a maximum of 30 kW (CW) or 50 kW (pulsed) through a water cooled coupling loop. A distributing capacitance of about 30 pf was added to the rf feeder so as to compensate the inductance of the input impedance. The amplitude of the field gradient in the RFQ cavity is stabilized by a feedback loop with a Double Balance Mixer.

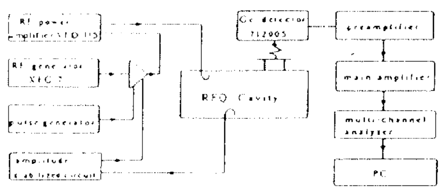

Fig. 3 RFQ with rf power and calibrated systems

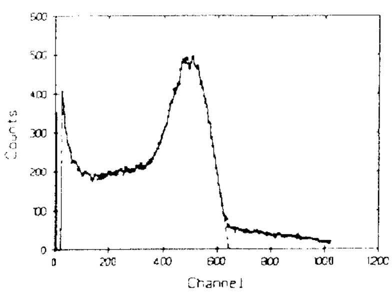

Fig. 4 X-ray spectrum at rf power of 42.5 kW

The voltage between the quadrupole electrodes is determined by the energy spectrum of Roentgen ray, which is produced by the electrons accelerated between the electrodes, at various rf power input level. High sensitive Ge-detector, which is calibrated by the characteristic γ-rays of appropriate isotopes including Am^{241} (59.54 keV) and Fe^{55} (5.9 keV), is used for this purpose. The layout of the RFQ voltage calibration system are illustrated in Fig. 3. Typical Roentgen ray spectrum at rf power of 42.5 kW is shown in Fig. 4, which corresponds to the designed operating voltage of 75 kV.

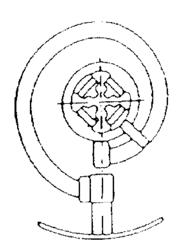

Fig. 5 Frequency adjustment by movable shorting bar

The operating frequency of ISR RFQ can be varied in the range of 24 - 40 MHz by moving a shorting bar on the spiral arm (see Fig. 5) [8]. The frequency of 26 MHz can be easily tuned by fixing the bars at a proper position of arms.

Table 2. ISR RFQ properties versus rf power

P_{in} kw	19.4	24.5	29.5	34.6	39.6	44.4
V kv	53.4	58.3	63.1	67.7	72.9	77.3
T_{Wat} °C	23.5	24.7	25.6	27	28.8	29.5
ρkΩm	132	125	121	119	121	121
f MHz	26.008	26.007	26.005	26.004	26.003	26.002

Typical properties of ISR RFQ versus rf power are listed in table 2. The very small frequency shift, low temperature rise of the cooling water, and efficient specific shunt impedance indicate that the ISR RFQ can operate stably and effectively under the designed conditions.

4. BEAM DYNAMICS CALCULATION

The beam dynamics of the ISR RFQ have been studied extensively. The code PARMTEQ was transferred from VAX to PC for this purpose, and it was upgraded to enable the instantaneous display of phase plots (x x'), (y y'), (Δ W Δϕ), beam envelopes as well as particle loss at each cell. Meanwhile, a code called OPTIMUM was developed to optimize the parameters in the sense of maximizing the current limit for both longitudinal and transverse motion. For the ISR RFQ, the typical results obtained by these computation is shown in Fig. 6. Under these parameters, the beam transport efficiency can be as high as 95 % for a N^+ beam accelerated from 20 keV up to 300 keV.

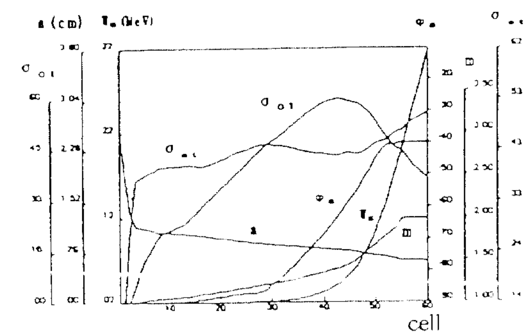

Fig. 6 Working parameters along axis

The 4 rod electrodes with trapezoidal profile (Fig. 7) were adopted in the preliminary beam test to simplify the machining of electrodes. For this sake, two kinds of electrodes, 4 -rod and mini-vane electrodes with two dimensional profile have been examined and compared with the ideal electrodes.[9] It was shown that the transverse and longitudinal phase advances are very close to each other.

5. BEAM TEST

The layout of the beam test is schematically shown in Fig. 8. The ion source is of side extraction PIG type with permanent magnet, which has been developed at Peking University[10].

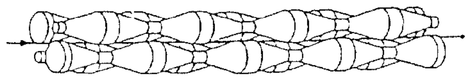

Fig. 7 4 Rod electrodes with trapezoidal profile

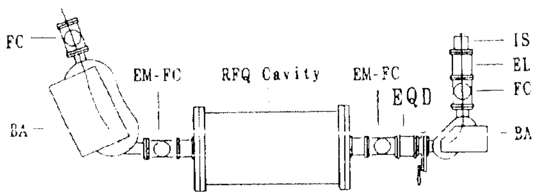

Fig. 8 The layout of the beam test

This source uses cold cathodes of LaB_6. With an arc voltage of 400-500 V and arc current of 150-200 mA, the extracted beam consists of over 80 % N^+ ions . Therefore, N^+ beam was injected into RFQ directly without analyzer in the first try. The energy of the accelerated N^+ beam was measured with the magnetic analyzer after the cavity. It is shown that the N^+ ions has been accelerated from 20 keV to 300 keV at an rf power of 25 kW with a duty factor of 1/6, and the average beam current is 1.7 μA. The measured time structure is shown in Fig. 9.

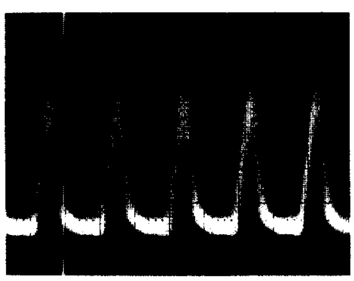

Fig. 9 Time structure of accelerated N^+ beam

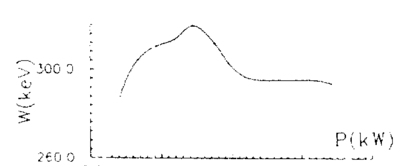

Fig. 10 Beam energy versus rf power

The accelerated beam energy, average beam current and energy spectrum were measured for N^+ ions at different rf power level. The results are shown in Fig. 10, 11 and 12. It appears that there are multi peaks at about 40 kW and 25 kW, respectively. To study the reason, a series of measurements and calculations will be further carried out.

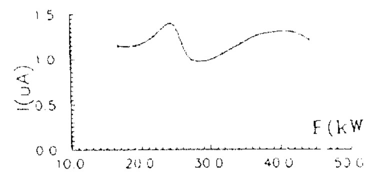

Fig. 11 Average beam current versus RF power

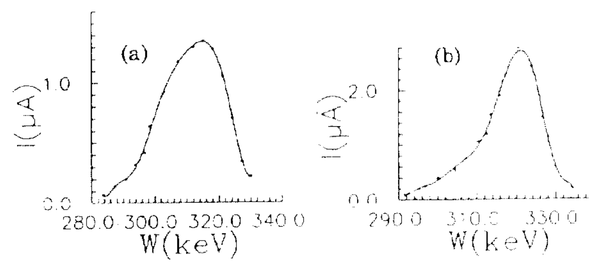

Fig. 12 Energy spectrum of accelerated N+ beam
(a) P = 40 kW (b) P = 25 kW

6. CONCLUSION

The preliminary beam test shows that the flexible ISR RFQ suits well to accelerate heavy ions, like N^+. The designed output energy of 300 keV has been achieved stably at an operating frequency as low as 26 MHz. The experiments and calculations to improve beam efficiencies and performance will be further carried out.

ACKNOWLEDGMENT

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